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Impacts of temperature and precipitation variability in the Northern Plains of the United States and Canada on the productivity of spring barley and oat

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ABSTRACT: Increasing temperatures and changes in precipitation are expected to effect a change in production of cool-season crops such as spring barley and oat. To determine whether observed changes may already have had an impact on these crops in the Northern Plains of the United States and Canada, first-differences of growing-season temperature and precipitation and of annual yield data were analysed via multiple linear regression for 1980–2012 for the genetically stable cultivars of 'Robust' spring barley (*Hordeum vulgare* L.) at three sites in Minnesota, and for 'Gopher' oats (*Avena sativa* L.) at five sites in Minnesota and neighbouring states and provinces. Temperature and precipitation impacts also were assessed for the top-three yielding barley and oat cultivars at each site to assess whether newer varieties responded similarly to the older varieties. Barley yield at the coolest site showed a modest relationship with climate while the warmer sites showed stronger relationships between climate variability and barley yield, particularly for negative impacts of high temperatures. Climate variability also had a significant impact on yield at the five oat sites. Warm pre-sowing temperatures enhanced yields at cooler sites while high temperatures later in the growing season reduced yields across the sites. Results for the top-three barley and oat cultivars often were similar to those for the older cultivars. Our results suggest that observed climate changes have contributed to the relative decrease in barley and oat yields in the region, that more recent releases have partially compensated for the negative impacts of observed temperature and precipitation trends, and that model projected changes in temperature and precipitation will continue to present both benefits and challenges for barley and oat production in the Northern Plains.

KEY WORDS barley; oat; crop yield; climate change; Minnesota

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1. Introduction

Climatic change is expected to have significant impacts on agriculture around the world. The Intergovernmental Panel on Climate Change Fourth Assessment Report (AR4) concluded that crop yields may increase 10–15% in the mid- to high- latitudes with rising CO_2 levels and a global average temperature increase of 1–2 °C relative to 1980–1999 (Easterling *et al.*, 2007). However, temperature increases of 2–3 °C will limit the yield increases of C_3 crops (such as barley, oat, and wheat) that result from elevated CO_2, and even larger temperature increases may offset CO_2 fertilization effects altogether.

Historical data on yield variability as related to climate have demonstrated how variations in temperature and precipitation can impact crop yields (e.g. Porter and Semenov, 2005; Lobell *et al.*, 2011; Peltonen-Sainio *et al.*, 2011). In general, increased temperatures have been observed to reduce yields for spring-planted small grains, including wheat, barley, and oat. Chmielewski and Köhn (1999) showed that barley and oat yields in Germany decreased when early-season temperatures were above normal. Schelling *et al.* (2003) found that high mean daily temperatures during the grain fill period, or between Zadoks growth stage 70 and 87 (Zadoks *et al.*, 1974), shortened that period and resulted in below-average barley and oat yields. Similar findings were reported by Trnka *et al.* (2004) using the CERES-Barley crop model with current and future modelled climate conditions representative of the Czech Republic. Ugarte *et al.* (2007), using data from Argentina, found that increased temperatures had the largest negative impacts on grain yield when they occurred during the stem elongation phase of crop development, or between Zadoks growth stage 31 and 45. Barley and oat in Finland (Peltonen-Sainio *et al.*, 2011) showed similar negative yield responses to high temperatures during the early- and mid-developmental phases, though barley yields responded positively to high temperatures closer to maturity. Lanning *et al.*

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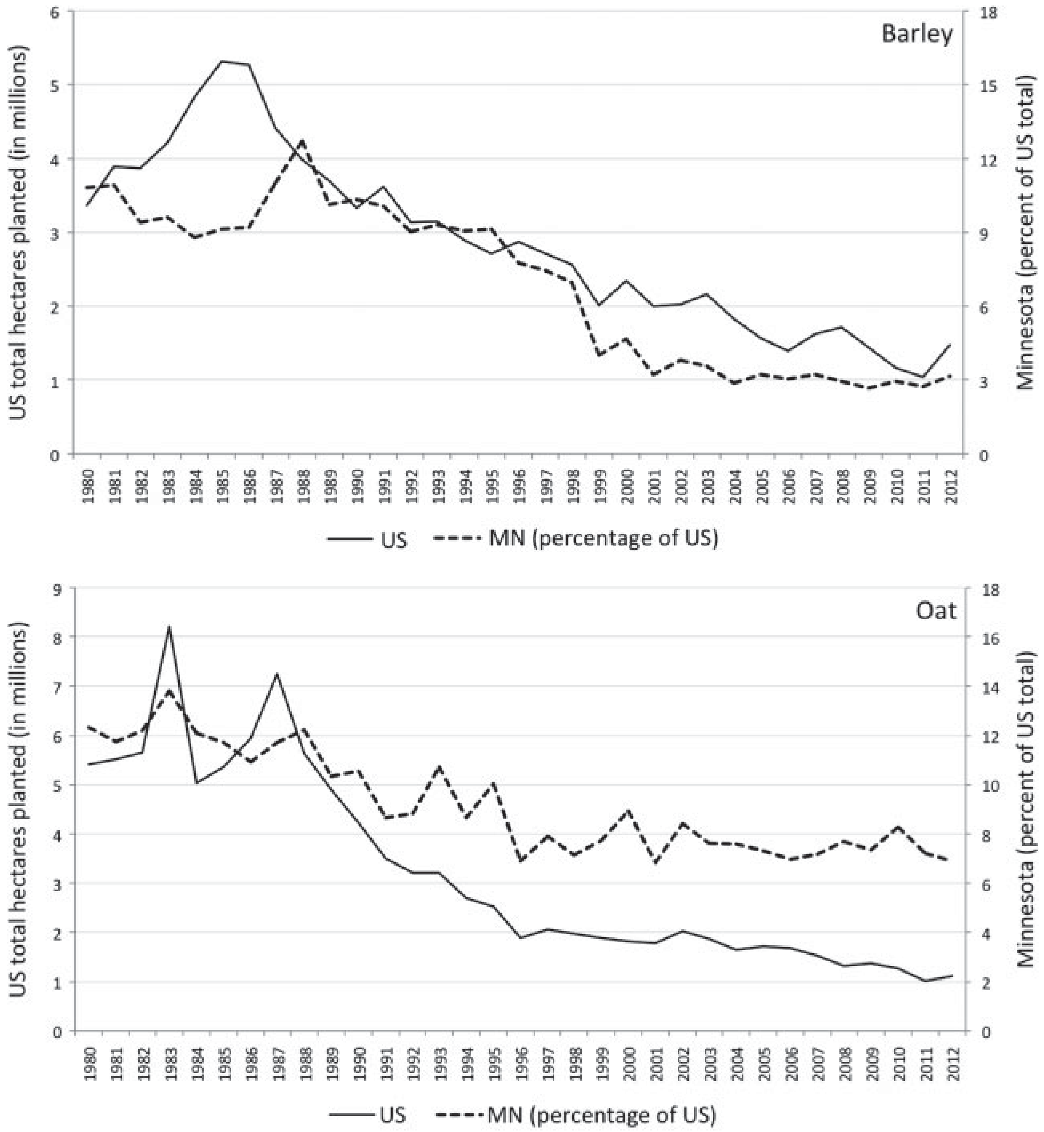

Figure 1. Total hectares of barley (top) and oat (bottom) planted in the United States (solid line) and the percentage of the total that is planted in Minnesota (dashed line). Data are from the National Agricultural Statistics Service (2013).

(2010) found that, for wheat in Montana, United States, higher temperatures in March (leading to earlier planting dates) were conducive to increased yields but that higher temperatures in July reduced yields, similar to the findings of Schelling *et al.* (2003).

While high temperatures, particularly during the middle of the growing season, almost always result in reduced yields, increases in precipitation can have both positive and negative impacts. Chmielewski and Köhn (1999) and Hakala *et al.* (2012) found that increased precipitation resulted in reduced yields if it occurred near the planting date but enhanced yields when it occurred 3–7 weeks after planting. In addition, Peltonen-Sainio *et al.* (2011) showed that high precipitation late in the growing season (near plant maturity) also had a negative impact on yield, possibly because of reduced grain quality (*cf* Hakala *et al.*, 2012).

Minnesota's climate warmed at a rate of about 0.6 °C over the 20th century; since the 1980s, however, the rate of temperature change has increased to about 3 °C per century (Zandlo, 2008). It is projected that by 2100 average temperatures in Minnesota could be higher by about 4 °C (1971–1999 baseline); summer averages are projected to increase slightly less than 4 °C, although the frequency of extreme hot days is expected to increase (Kunkel *et al.*, 2013). Precipitation in the state has increased slightly over the 20th century, with some increase also in the frequency of heavy precipitation events over the past several decades (Zandlo, 2008). Annual average precipitation is expected to be about 10% higher by 2100, although summers are expected to have only slightly higher precipitation compared with the 1971–1999 baseline precipitation (Kunkel *et al.*, 2013).

Minnesota has historically been an important state for producing oats and six-row malting barley but the acreage of both crops has been declining in the state (and in the United States overall; Figure 1). There are likely a number of reasons for these declines, including better

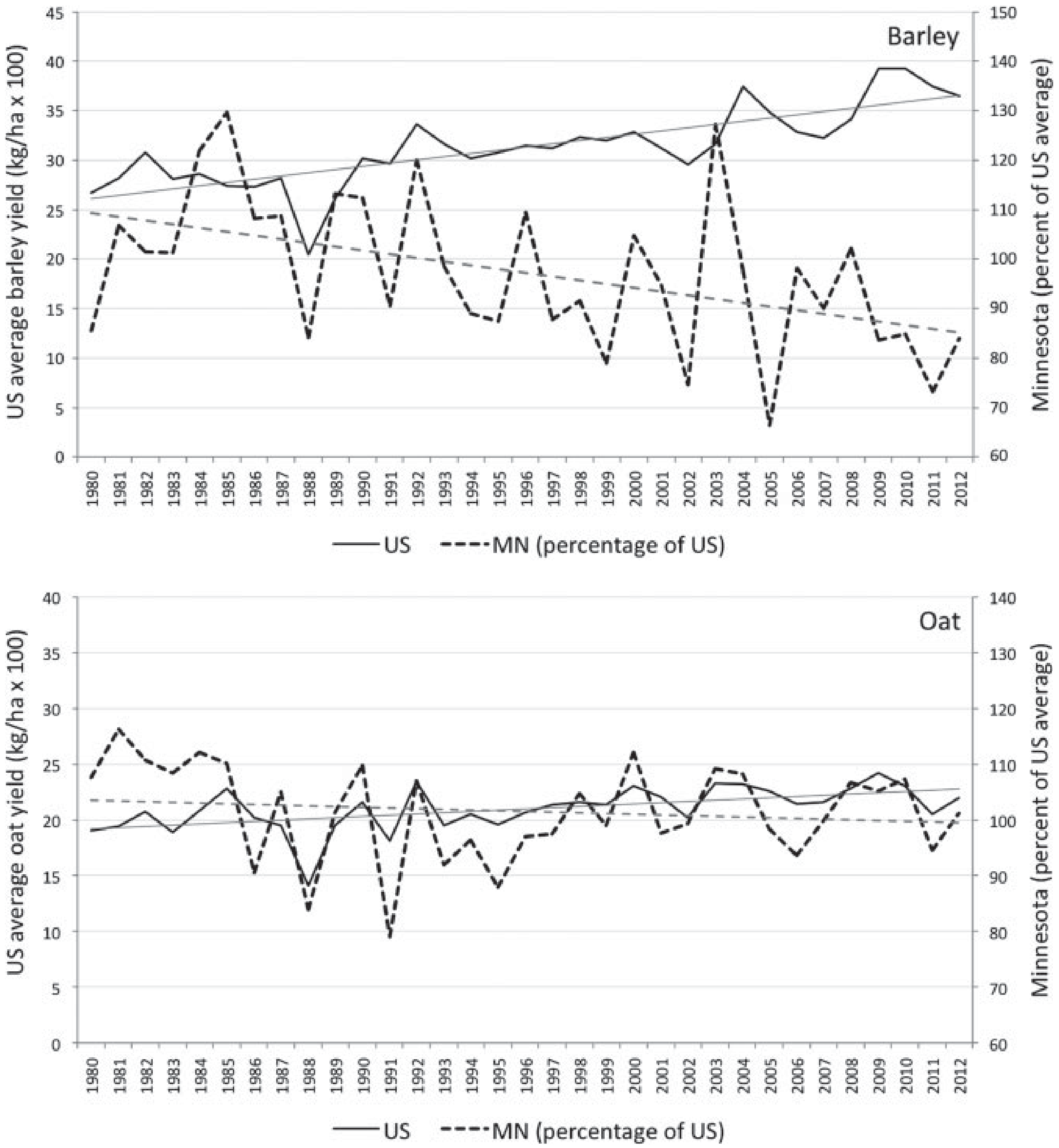

Figure 2. Average yield of barley (top) and oat (bottom) in the United States (solid line) and the Minnesota average yield as a percentage of the U.S. average (dashed line). Linear trends for the 33-year period also are shown. Data are from the National Agricultural Statistics Service (2013).

economic returns for other commodities such as soybeans and corn, changes in federal farm policies, emerging disease problems such as the outbreak of Fusarium head blight in the early- and mid-1990s (McMullen *et al.*, 1997), and a decline in demand for bedding straw as livestock numbers have declined sharply.

Between 1980 and 2012, US average oat yield increased at a rate of 11.2 kg ha^{-1} $year^{-1}$ and barley yield increased by 32.6 kg ha^{-1} $year^{-1}$ (Figure 2). Minnesota oat and barley yields also increased over this time period, but did so at a slower rate: 8.7 kg ha^{-1} $year^{-1}$ for oat and 6.54 kg ha^{-1} $year^{-1}$ for barley. When compared with their respective national averages, then, Minnesota had gains in oat yield that are about 4% smaller than (though not statistically different from) the United States as a whole, whereas the gain in Minnesota barley yields was 24% smaller than (and statistically different from) the United States as a whole (Figure 2). Given the extensive evidence that temperature and precipitation variability can have significant effects on the yields of small grains, changes in the observed climate may have contributed to the decline of barley and oat acreage and slower pace of yield improvements in Minnesota and the surrounding region.

The objectives of this research are to explore whether the temperature and precipitation trends that have been observed in and around Minnesota have had an impact on past productivity of oat and barley. We analyse the barley cultivar 'Robust' (*Hordeum vulgare* L., PI 476976; Rasmusson and Wilcoxson, 1983) and the oat cultivar 'Gopher' (*Avena sativa* L., CI 2027, Minnesota no. 674; Stanton, 1955) as well as the top-three yielding barley and oat cultivars in any given year. Inclusion of the latter provides some insight as to whether newer varieties

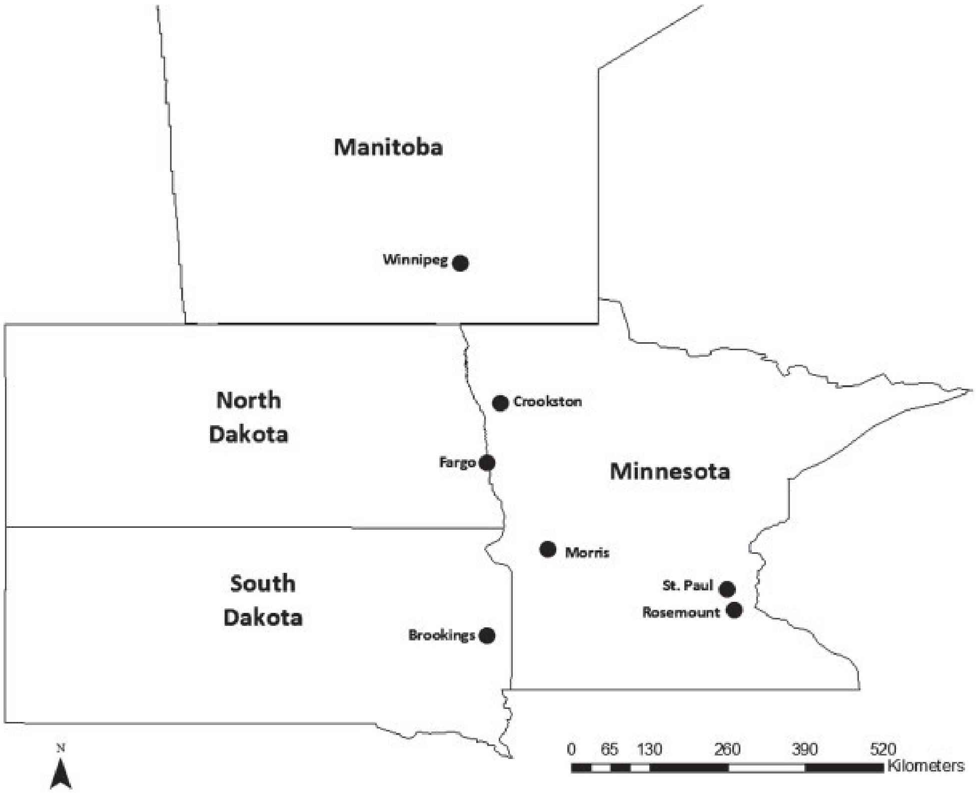

Figure 3. Locations of sites used in this study

are more or less sensitive to climate trends when compared with varieties developed before the increased rate of warming that began in the 1980s (Zandlo, 2008). Both barley and oat are self-pollinating species so the cultivars Robust and Gopher can be considered genetically stable over generations. Differences in year-to-year performance are the result of the genotype × environment interaction and trends in the regression analyses therefore suggest that changes in climate either positively or negatively impact the performance of the individual cultivars. Using the regression results, we then describe how past and projected future changes in temperature and precipitation create both benefits and challenges to barley and oat production in the region.

2. Data and methods

The Minnesota Agricultural Experiment Stations conduct annual performance trials on spring barley, and the University of Minnesota in collaboration with the U.S. Department of Agriculture coordinates a multi-state oat performance trial. The barley data used in this research were taken from yield trials at the Northwest Agricultural Experiment Station in Crookston, Minnesota (MN), the West Central Agricultural Experiment Station in Morris MN, and the University of Minnesota Agricultural Experiment Station in St. Paul (Figure 3 and Table 1). For oat, we used annual yield data from the uniform regional performance nurseries in Morris and Rosemount, MN; Brookings South Dakota (SD); Fargo North Dakota (ND);

Table 1. Location and length of record at each site for the analysis period 1980–2012.

	Latitude and longitude and elevation	Length of record and (in parentheses) the number of missing years
Barley		
Crookston, MN	47.8°N, 96.6°W, 271 m	28 (5)
Morris, MN	45.6°N, 95.9°W, 347 m	29 (4)
St Paul, MN	45.0°N, 93.2°W, 297 m	24 (9)
Oat		
Winnipeg, MB	49.9°N, 97.2°W, 239 m	29 (4)
Fargo, ND	46.9°N, 96.8°W, 274 m	31 (2)
Brookings, SD	44.3°N, 96.8°W, 500 m	32 (1)
Morris, MN	45.6°N, 95.9°W, 347 m	30 (3)
Rosemount, MN	44.7°N, 93.1°W, 290 m	32 (1)

MN, Minnesota; MB, Manitoba; ND, North Dakota; SD, South Dakota. Station locations are shown in Figure 3.

and Winnipeg Manitoba (MB) (Figure 3 and Table 1). Time series of annual barley (Figure 4) and oat yields (Figure 5) show substantial year-to-year variability. We focused on grain yield for our analysis because most other agronomic data such as planting date, heading date, harvest date, lodging (the tendency for crops to bend over), and/or incidence and severity of disease or pest problems had too much missing data. The methods for conducting the yield trials have not changed substantially over the past three decades as seedbed preparation, fertilizer

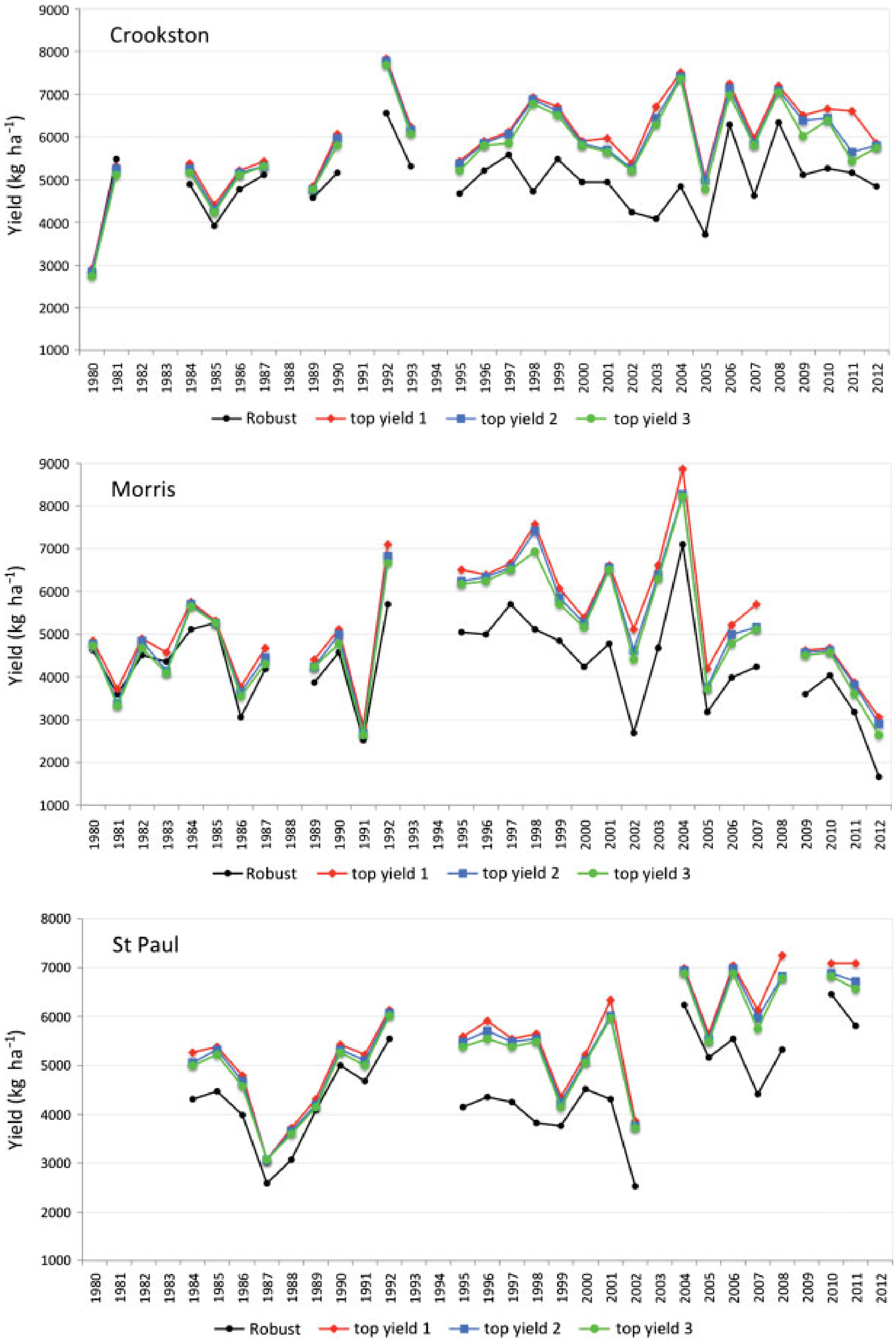

Figure 4. Annual barley yield at Crookston, Morris, and St. Paul, Minnesota. Yields shown are for the barley cultivar ‘Robust’ and for the top-three yielding barley cultivars in a given year (excluding Robust).

application, weed control, and seeding and harvest techniques have remained much the same.

The variables chosen to represent climate variability were mean monthly maximum and minimum temperature and total precipitation for growing-season months (April to July for US sites, May to August for Winnipeg). These variables were selected based on information in Chmielewski and Köhn (1999) and Wiersma and Ransom (2005). Precipitation from the prior winter also was included because spring snowmelt can be an important source of additional growing-season moisture (Baker *et al.*, 1979). We did not calculate growing degree-days or temperature and precipitation during specific growth phases because planting date and growth-stage information often was missing from the yield trials databases. Monthly temperature and precipitation data for the US

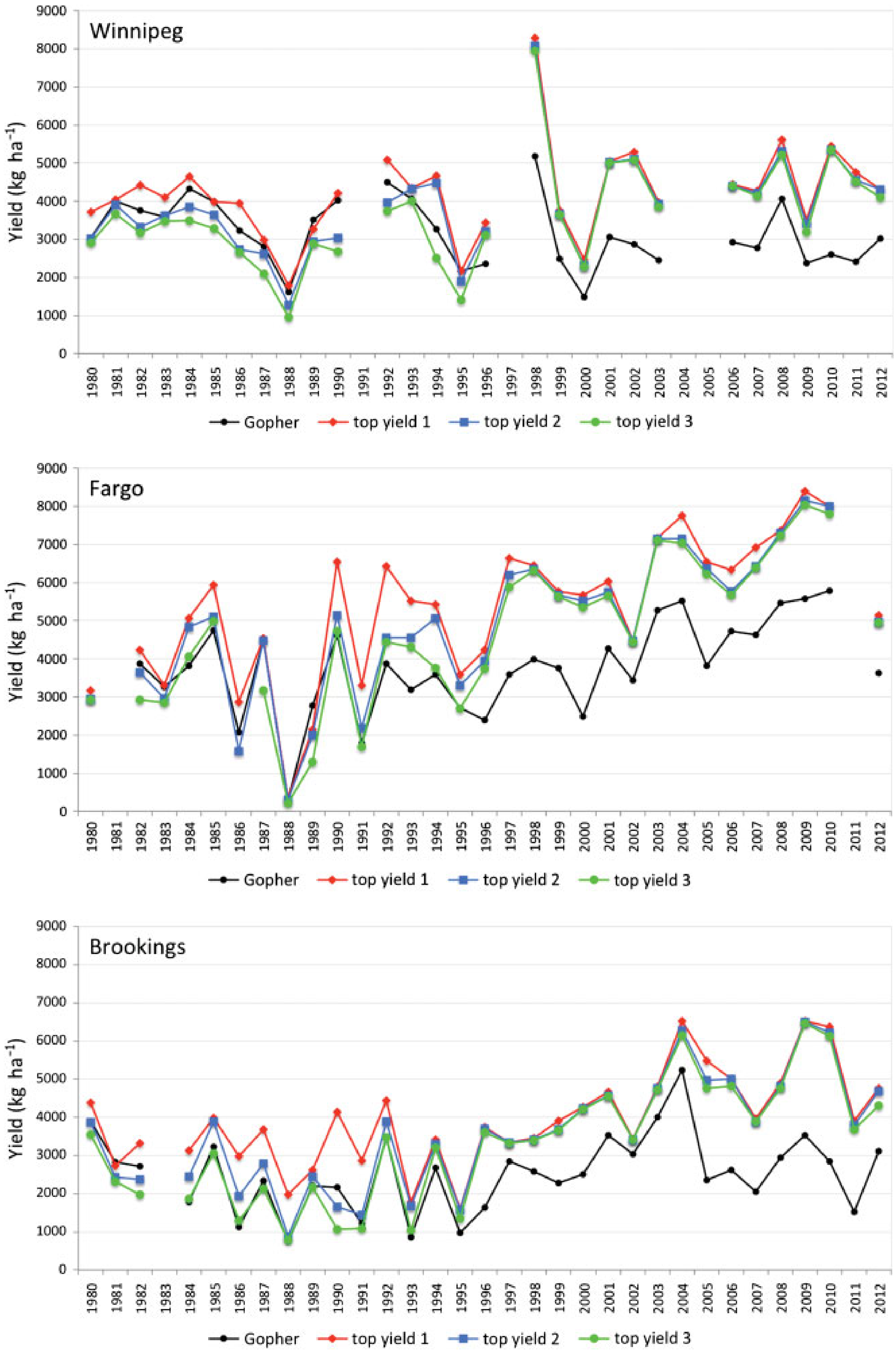

Figure 5. Annual oat yield at Winnipeg, Manitoba; Fargo, North Dakota; Brookings, South Dakota; and Rosemount and Morris (both in Minnesota). Yields shown are for the oat cultivar 'Gopher' and for the top-three yielding oat cultivars in a given year (excluding Gopher).

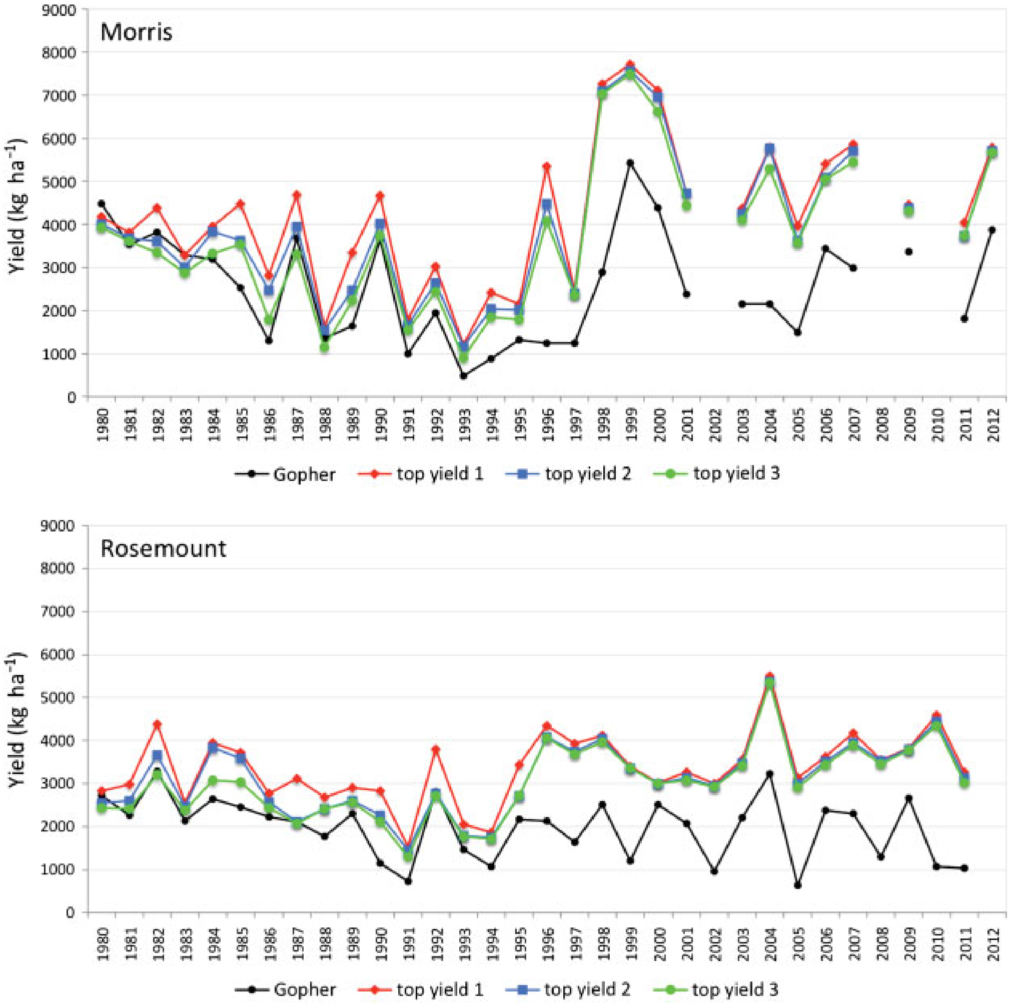

Figure 5. Continued

sites were compiled from the U.S. Global Historical Climatology Network's Monthly Summaries database (Lawrimore *et al.*, 2011, National Climatic Data Center, 2013); data for Winnipeg were compiled from Environment Canada's National Climate Data and Information Archive (Environment Canada, 2013). Mean growing-season temperature and precipitation and accumulated winter precipitation at each site are given in Table 2.

Following Lobell *et al.* (2005) and Lobell and Field (2007), we employ a first-difference methodology to separate the effects on yield of year-to-year changes in temperature and precipitation ('climate variability') from the effects on yield of long-term trends in these same variables ('climate change'). In addition, we performed regression analyses using the yearly (nondifferenced) yield and climate variables, and using linearly detrended

Table 2. Mean 1980–2012 growing-season maximum and minimum temperature and precipitation (April to July for US sites, May to August for Winnipeg) and accumulated winter precipitation (November to March for US sites, November to April for Winnipeg) at sites used in this study.

	Winnipeg, MB	Fargo, ND	Crookston, MN	Brookings, SD	Morris, MN	St Paul, MN	Rosemount, MN
Mean growing season Tx	23.4	21.8	20.8	21.4	21.4	22.7	22.7
Mean growing season Tm	10.1	9.0	8.1	8.8	9.3	11.3	10.2
Mean growing season P	298.8	271.8	270.1	326.7	331.8	391.6	388.8
Mean accumulated winter P	137.0	110.8	84.5	77.3	115.2	151.8	162.7

MN, Minnesota; MB, Manitoba; ND, North Dakota; SD, South Dakota; Tx, maximum temperature (°C); Tm, minimum temperature (°C); P, precipitation (mm).
Data for US sites are from the U.S. Global Historical Climatology Network (Lawrimore *et al.*, 2011; National Climatic Data Center, 2013); data for Winnipeg are from Environment Canada's National Climate Data and Information Archive (Environment Canada, 2013).

yield and climate variables. All three methods gave qualitatively similar results. The first-difference approach more clearly distinguishes the effects of variability from those due to trend so we present only those results herein.

The effects of temperature and precipitation variability on barley and oat yields were assessed via multiple linear regression with MATLAB (MathWorks, 2012). We use a linear regression because scatterplots of yield *versus* monthly maximum and minimum temperature, total monthly precipitation, and accumulated winter precipitation (both yearly data and first-differences) showed little to no discernable nonlinear patterns. Although yield can respond nonlinearly over some ranges of temperature and precipitation (e.g. Porter and Semenov, 2005; Schlenker and Roberts, 2009), this did not appear to be the case for the mean monthly values used here. Our use of a linear model also allows us to compare our results with prior crop-climate research (e.g. Chmielewski and Köhn, 1999; Peltonen-Sainio *et al.*, 2011; Hakala *et al.*, 2012).

For each study site, the dependent variable was the first-difference of annual barley or oat yield at the site ($\Delta\text{Yield} = \text{Yield}_n - \text{Yield}_{n-1}$ where $n = \text{year}$). Independent (predictor) variables were the first-differences of mean maximum ($\Delta\text{Tx} = \text{Tx}_n - \text{Tx}_{n-1}$) and minimum ($\Delta\text{Tm} = \text{Tm}_n - \text{Tm}_{n-1}$) temperature and total precipitation ($\Delta P = P_n - P_{n-1}$) for each month of the growing season, as well as accumulated precipitation for the prior winter ($\Delta\text{WinterP} = \text{WinterP}_n - \text{WinterP}_{n-1}$). The analysis used MATLAB's interactive stepwise multiple regression option in order to maximize variance explained (adjusted r^2) while simultaneously minimizing multicollinearity among the predictor variables selected for inclusion in the regression model. For all selected models, the variance inflation factor is less than 1.4.

3. Barley yield and climate variability

3.1. Temperature and precipitation effects on yield of Robust barley

For the period 1980–2012, the stepwise regression model showed that both temperature and precipitation variability affected yields of Robust barley (Table 3). The explained

Table 3. Regression coefficients, standard errors (in parentheses), and model statistics for the stepwise multiple linear regression results for the barley sites.

	Crookston, MN		Morris, MN		St Paul, MN	
	Robust	Average of top three varieties	Robust	Average of top three varieties	Robust	Average of top three varieties
ΔMay Tx	−181.55 (77.74) *−536.75*					
ΔJun Tx					−142.09 (33.36) *−349.79*	−172.05 (40.31) *−423.55*
ΔJun Tm		−232.58 (115.82) *−472.02*	−347.33 (86.75) *−752.90*	−397.14 (92.71) *−860.87*		
ΔJul Tm					−101.58 (47.80) *−181.79*	−132.38 (57.76) *−236.92*
ΔWinter P			7.20 (3.23) *420.40*	7.25 (3.46) *422.77*		
ΔApr P					4.81 (1.34) *301.25*	7.27 (1.62) *454.95*
ΔJun P	−5.57 (3.12) *−409.75*					
ΔJul P			−6.67 (3.06) *−413.73*	−7.98 (3.27) *−494.94*		
r^2	0.255	0.161	0.483	0.513	0.564	0.608
Adjusted r^2	0.180	0.121	0.428	0.461	0.518	0.566
p-Value	0.0526	0.0577	0.0003	0.0001	<0.0001	<0.0001

Tx, maximum temperature; Tm, minimum temperature; P, precipitation; MN, Minnesota.
The dependent variable in each regression model is the change in annual barley yield ($\Delta\text{Yield} = \text{Yield}_n - \text{Yield}_{n-1}$ where $n = \text{year}$) (kg ha^{-1}) for the cultivar 'Robust' and for the average of the top-three yields at the site regardless of cultivar (Robust excluded). Units for the regression coefficients are kg ha^{-1} per °C or per mm for temperature- and precipitation-predictors, respectively.
A blank cell indicates that the variable was not a statistically significant predictor of ΔYield at that site.
Standardized coefficients (dimensionless; in italics) indicate the relative importance of each variable when more than one predictor is included in the regression model.

variance (adjusted r^2) was smallest at Crookston (the coolest barley site, with 18% explained variance) and largest at St. Paul (the warmest barley site, with 52% explained variance). At Crookston, yields are higher when May maximum temperature and June precipitation are reduced. Planting at Crookston typically occurs in mid- to late-April (Wiersma and Ransom, 2005) and high temperatures early in the growing season can reduce the number of tillers and/or the panicle size (Chmielewski and Köhn, 1999), both of which can reduce yield. High June precipitation may result in waterlogging (*cf* Hakala *et al.*, 2012), which hampers plant growth and thus yield (Setter and Waters, 2003).

At Morris and St. Paul, the regression model identifies higher temperatures in June and July as strong contributors to reduced yields. Planting at these sites usually occurs in early- to mid-April. Tiller formation and the initiation of the number of spikelets thus will typically occur by mid-May, with grain fill starting in the second week of June and being completed by mid-July. High temperatures have been found to reduce tillering, grain number, and grain weight, which can reduce yield (Savin and Nicholas, 1996; Chmielewski and Köhn, 1999; Hakala *et al.* 2012). High maximum temperatures may shorten the duration of grain fill and/or reduce grain weight, thus reducing yield (Altenbach *et al.*, 2003; Hakala *et al.* 2012), while high minimum temperatures can increase night-time respiration (Peng *et al.*, 2004; Mohammed and Tarpley, 2009) thereby reducing the amount of synthate available for plant growth and development.

The regression model identified increased precipitation in winter (for Morris) and in April (for St. Paul) as beneficial to yield. Higher accumulated wintertime or early-season (April) precipitation may increase yields by increasing the available soil moisture during the vegetative phase of crop development while still keeping the soils dry enough for planting. In contrast, increased July precipitation at Morris is a strong contributor to reduced yield. July is near harvest time at Morris and high precipitation can contribute to lodging, making harvesting more difficult and thus reducing yield (Schelling *et al.*, 2003; Wiersma and Ransom, 2005). This finding is similar to that of Peltonen-Sainio *et al.* (2011), who found that increased early-season precipitation typically enhanced the yields of spring cereals while increased late-season precipitation typically reduced them.

3.2. Robust *versus* the top-three yielding barley cultivars

Annual yields of the top-three barley cultivars are highly correlated at each site (Figure 4) so we used the first-difference of the average of the top-three yields as the dependent variable in the stepwise regression analysis. Despite allowing the cultivars to change from year to year, the regression models for Morris and St. Paul identified the same important climate variables as for the cultivar Robust, while at Crookston yields of the top-three cultivars are sensitive only to changes in June minimum temperatures (Table 3). The low adjusted r^2 value for Crookston suggests that the newer (post-1980) cultivars are less sensitive to temperature and precipitation variability at this site than is the older cultivar Robust. At Morris and St. Paul, however, the adjusted r^2 values for the newer cultivars are similar to those for Robust. Overall, regression results from the top-three yielding cultivars show that high maximum and minimum temperatures during the middle and later phases of plant development are important factors in reducing yields across all three sites.

3.3. Effects of observed trends in temperature and precipitation for barley yield

We used the regression models at each site and for each cultivar (Robust and top-three average) to estimate how observed trends in temperature and precipitation for 1980–2012 have affected yields over this same time period. We multiplied the coefficients for each climate variable that appeared in the regression model (Table 3) by their observed linear trends (Table 4) to estimate the change in yield that can be attributed to long-term temperature and precipitation change over this period (Table 5). We found that the effect on yield of observed temperature and precipitation trends varied across the sites. At Crookston, these trends have helped to enhance Robust yields, primarily due to the substantial decline in May maximum temperature; top-three yields, however, have been slightly reduced as a result of increasing June minimum temperatures. At Morris, both Robust and top-three yields have been depressed by the increase in June minimum temperature, which overwhelms the positive effects of reduced July precipitation and increased winter precipitation. In contrast, climate trends have slightly

Table 4. Linear trends in temperature and precipitation for the variables included in the multiple regression models for each barley site.

	Linear trend (1980–2012)
Crookston, MN	May Tx: −3.12 °C
	Jun Tm: 0.69 °C
	Jun P: 3.04 mm
Morris, MN	Jun Tm: 2.08 °C
	Winter P: 7.54 mm
	Jul P: −13.04 mm
St. Paul, MN	Jun Tx: −0.25 °C
	Jul Tm: 0.48 °C
	Apr P: 14.86 mm

Tx, maximum temperature; Tm, minimum temperature; P, precipitation; MN, Minnesota.
Trends are in °C or mm per 33 years (1980–2012).

Table 5. Average barley yields (1980–2012) at each site and the estimated effect on yield of observed temperature and precipitation trends over the same time period.

	Crookston, MN		Morris, MN		St Paul, MN	
	Robust	Average of top three varieties	Robust	Average of top three varieties	Robust	Average of top three varieties
Average yield (kg ha^{-1})	4955	5856	4291	5143	4510	5420
Temperature/precipitation trend effect on yield (kg ha^{-1})	549	−160	−581	−667	58	88

MN, Minnesota.
The effect on yield is estimated by multiplying the linear trend in temperature and precipitation in Table 4 by the respective regression coefficients in Table 3.

enhanced yields at St. Paul because the positive effects of reduced June maximum temperature and increased April precipitation are larger than the negative impact of the increase in July minimum temperature. Although yields of the top-three cultivars are consistently higher on average than for the older cultivar Robust (Table 5, Figure 4), this analysis shows that the yields of newer cultivars could have been even higher in the absence of the negative effects of temperature and precipitation trends at these sites.

4. Oat yield and climate variability

4.1. Temperature and precipitation effects on yield of Gopher oat

Historical climate variability also had a significant effect on yields of Gopher oat. Precipitation and especially temperature variability were able to account for about 12% of the variation (adjusted r^2) in yields at Winnipeg, about 30% of the variance at Fargo and Morris, and over 50% of the variance at Brookings and Rosemount (Table 6). Increased temperatures in April promote higher yields at Fargo and Brookings (colder sites) but higher temperatures in June and/or July at all sites except Morris are strong contributors to reduced yields. Increased April temperatures at Fargo and Brookings help to warm the soils and enhance drying after spring snowmelt (Potter, 1956; Jin *et al.*, 2008). This allows for earlier planting (planting at these sites typically is in late April to early May, Wiersma and Ransom, 2005), which in turn allows plants to develop and mature before the higher temperatures typically experienced in mid- to late summer. In contrast to the positive effect on yield of increased pre-sowing (April) temperatures, increased maximum June temperatures at Winnipeg, where planting occurs in early- to mid-May, are associated with reduced yields (Table 6). High temperatures early in the growing season can stress the plant by reducing both the number of tillers and the panicle size (Chmielewski and Köhn, 1999). Peltonen-Sainio *et al.* (2011) similarly found that high temperatures during plant establishment and early growth resulted in decreased yields at a range of sites in Finland.

At Fargo, Brookings, and Rosemount, increases in temperature in the mid- to late-growing season were strongly associated with reduced yield (Table 6). This finding is consistent with Peltonen-Sainio *et al.* (2011) who showed that high temperatures during their growth stages 2 and 3 (just prior to heading through early grain filling) were strong contributors to reduced crop yields. This reduction likely is due to a decrease in the length of the grain-filling period and/or to an increase in the number of days with temperatures approaching physiological threshold temperatures for oat (Wiersma and Ransom, 2005; Peltonen-Sainio *et al.*, 2011; Hakala *et al.*, 2012). Schelling *et al.* (2003) also showed that grain yield decreased when the duration of grain filling was shortened due to higher temperatures during the grain filling period (late June to July for these sites). In addition, higher minimum temperatures can increase night-time respiration (Peng *et al.*, 2004; Mohammed and Tarpley, 2009), reducing the amount of photosynthate available for growth thereby ultimately reducing grain yield.

Precipitation variability emerged as an important variable affecting yields of Gopher oat at Brookings and Morris (Table 6). Unlike the results for barley, both early- and late-season increases in precipitation were detrimental to oat yield. Increased May precipitation at Brookings may lead to waterlogging or partial submergence of plant shoots in the clay loam soils typical of this site (Soil Survey Staff, 2013). Increased April precipitation at Morris can make soils too wet for planting. Delayed planting is associated with reduced yield (also noted by Hakala *et al.*, 2012), likely due to the resultant increase in developmental rates (Peltonen-Sainio *et al.*, 2011). Increased July precipitation also has a strong negative effect on yield at Morris, possibly due to lodging (Schelling *et al.*, 2003; Wiersma and Ransom, 2005).

4.2. Gopher *versus* the top-three yielding oat cultivars

As for barley, annual yields of the top-three oat cultivars are highly correlated at each site (Figure 5) so we used the first-difference of the average of the top-three yields as the dependent variable in the stepwise regression analysis (Table 6). Temperature and precipitation variability can account for over 45% of the variance in top-three yields at the US sites. At Winnipeg (the northernmost site), however, the top-three average yield showed no discernable relationship with winter precipitation or growing-season climate. Increased April temperatures remain important contributors to higher yield at Fargo and Brookings

Table 6. Regression coefficients, standard errors (in parentheses), and model statistics for the stepwise multiple linear regression results for the oat sites.

	Winnipeg, MB*		Fargo, ND		Brookings, SD		Morris, MN		Rosemount, MN	
	Gopher	Average of top three varieties	Gopher	Average of top three varieties	Gopher	Average of top three varieties	Gopher	Average of top three varieties	Gopher	Average of top three varieties
ΔApr Tx				178.36 (73.53) *646.41*	104.47 (49.89) *367.20*	169.66 (49.89) *596.32*				
ΔApr Tm			195.34 (113.75) *450.31*							
ΔJun Tx	−173.78 (81.89) *−414.55*			−193.80 (106.50) *−506.62*				−307.40 (72.07) *−762.41*		
ΔJun Tm			−325.47 (95.34) *−895.25*		−258.96 (83.10) *−592.78*				−119.23 (34.33) *−507.25*	−122.67 (30.98) *−521.89*
ΔJul Tx				−525.31 (161.62) *−946.62*		−451.18 (146.89) *−881.35*				
ΔJul Tm					−247.19 (99.21) *−474.12*				−241.10 (78.71) *−447.32*	−133.35 (71.04) *−247.41*
ΔWinter P								−7.77 (3.09) *−453.68*		
ΔApr P							−7.26 (3.65) *−387.62*			
ΔMay P					−6.16 (2.87) *−372.24*					
ΔJul P							−9.91 (3.14) *−614.38*	−14.02 (2.90) *−869.08*		
r^2	0.164	–	0.346	0.536	0.604	0.611	0.397	0.651	0.547	0.503
Adjusted r^2	0.127	–	0.294	0.478	0.541	0.582	0.355	0.614	0.515	0.469
p-Value	0.0448	–	0.0049	0.0003	<0.0001	<0.0001	0.0007	<0.0001	<0.0001	<0.0001

MN, Minnesota; ND, North Dakota; SD, South Dakota; Tx, maximum temperature; Tm, minimum temperature; P, precipitation.
The dependent variable in each regression model is the change in annual oat yield (ΔYield = Yield$_n$ − Yield$_{n-1}$ where n = year) (kg ha^{-1}) for the cultivar ‘Gopher’ and for the average of the top-three yields at the site regardless of cultivar (Gopher excluded). Units for the regression coefficients are kg ha^{-1} per °C or per mm for temperature- and precipitation-predictors, respectively.
A blank cell indicates that the variable was not a statistically significant predictor of ΔYield at that site.
Standardized coefficients (dimensionless; in italics) indicate the relative importance of each variable when more than one predictor is included in the regression model.
*April temperature is not a candidate predictor variable for Winnipeg; April precipitation is part of Winnipeg’s accumulated winter precipitation.

whereas increased June and July temperatures are detrimental to yield. Precipitation variability emerges as an important factor affecting top-three yields only at Morris. Increased accumulated winter precipitation (and subsequent spring melt) may delay planting, and increased July precipitation can contribute to lodging; both of these factors would reduce yield. Interestingly, the negative impact of increased winter precipitation on top-three oat yield is opposite that to found for top-three barley yield at this same location. Overall, the regression results suggest that – with the exception of Winnipeg – the top-three yielding oat cultivars remain sensitive to temperature and precipitation variability, potentially even more so than the older Gopher cultivar as estimated by the adjusted r^2 values for Fargo, Brookings, and Morris (Table 6).

4.3. Effects of observed trends in temperature and precipitation for oat yield

We used the regression models at each site and for each cultivar (Gopher and top-three average) to estimate how observed trends in temperature and precipitation for 1980–2012 have affected oat yields over this same time period. We derive our estimates using the procedure described in Section 3.3 but using the regression coefficients in Table 6 and the observed linear trends in Table 7. The change in oat yield that can be attributed to long-term temperature and precipitation change over this period is given in Table 8. As occurred for barley, observed temperature and precipitation trends had both positive and negative effects on oat yield. Climate trends depressed yields at Fargo, Brookings, and Rosemount, largely due to increases in June and July maximum and (especially) minimum temperatures over this time period (Table 7). Climate trends enhanced yields at Morris, where the reduction in July precipitation increased yields more than other factors reduced them. Although yields of the top-three cultivars are consistently higher on average than for the older cultivar Gopher (Table 8, Figure 5), the newer varieties remain sensitive to climate variability at all sites except Winnipeg. Our results also suggest that yield gains for newer varieties would have been substantially larger at several of these sites if not for the negative effects of, in particular, the increasing trend in temperature.

5. Summary and conclusions

The present research indicates that temperature and precipitation variability and change over the past 33 years (1980–2012) has had a significant impact on barley and oat yields in Minnesota and surrounding regions. Warming temperatures, particularly in mid-growing season, have reduced yields at nearly all sites; increased precipitation benefited yields for some time periods and locations but was detrimental to yield at others. Yield effects (as represented by adjusted r^2 values) are stronger at climatologically warmer sites as compared with cooler sites, possibly because at the warmer sites oat and barley may be growing nearer their physiological limit. This observation echoes the findings of Lobell *et al.* (2011) who noted that crop yields in climatically warm countries were more sensitive to temperature increases than yields in cooler countries, and Hakala *et al.* (2012) found that barley cultivars from lower latitudes (than Finland) were the most sensitive to high temperatures. Over time this may mean that the southern edge of the viable area of oat and barley production creeps northward, and that barley and oat may disappear from the landscape in favour of better adapted species such as corn.

Similar to the results of Peltonen-Sainio *et al.* (2011), we find that the effects of temperature increases are consistent across the sites whereas the effects of precipitation are more variable. The higher frequency of temperature as compared with precipitation in the regression models shows that temperature variability dominates precipitation, which was also noted by Lobell *et al.* (2011).

Table 7. Linear trends in temperature and precipitation for statistically significant variables included in the multiple regression models for each oat site.

	Linear trend (1980–2012)
Winnipeg, MB	Jun Tx: −0.02 °C
Fargo, ND	Apr Tx: −0.59 °C
	Jun Tx: 0.75 °C
	Jul Tx: 0.36 °C
	Apr Tm: 1.45 °C
	Jun Tm: 1.65 °C
Brookings, SD	Apr Tx: 0.04 °C
	Jul Tx: 0.83 °C
	Jun Tm: 1.95 °C
	Jul Tm: 2.02 °C
	May P: 54.75 mm
Morris, MN	Jun Tx: −0.10 °C
	Winter P: 7.54 mm
	Apr P: 12.51 mm
	Jul P: −13.04 mm
Rosemount, MN	Jun Tm: 2.28 °C
	Jul Tm: 1.59 °C

MN, Minnesota; MB, Manitoba; ND, North Dakota; SD, South Dakota; Tx, maximum temperature; Tm, minimum temperature; P, precipitation.
Trends are in °C or mm per 33 years (1980–2012).

Temperature and precipitation variability and change are not the only environmental factors that can affect barley and oat yield. Cool and moist conditions early in the growing season, for example, increase the potential for lodging later in the season. Crown rust in oat requires mild to warm (20–25 °C) sunny days and mild nights (15–20 °C) with adequate moisture for dew formation. Therefore, in years that were favourable for, for

Table 8. Average oat yields at each site for 1980–2012 and the estimated effect on yield of temperature and precipitation trends over the same time period.

	Winnipeg, MB		Fargo, ND		Brookings, SD		Morris, MN		Rosemount, MN	
	Gopher	Average of top three varieties	Gopher	Average of top three varieties	Gopher	Average of top three varieties	Gopher	Average of top three varieties	Gopher	Average of top three varieties
Average yield (kg ha^{-1})	3169	3887	3753	4980	2527	3607	2560	3929	1970	3159
Temperature/precipitation trend effect on yield (kg ha^{-1})	3	–	−254	−440	−1337	−368	38	155	−655	−492

MN, Minnesota; MB, Manitoba; ND, North Dakota; SD, South Dakota.
The effect on yield is estimated by multiplying the linear change in temperature and precipitation listed in Table 7 by the respective regression coefficients listed in Table 6.

example, lodging or crown rust, the effects of temperature and precipitation are potentially confounded with the incidences of these biotic stresses. Nonetheless, the similarity in statistical results across sites (as discussed in Sections 3 and 4) provides support for our interpretation of climate variability and change as an important region-wide factor influencing yield.

In many cases our regression analysis identified the same temperature and precipitation stresses as important for both the two older cultivars and the newer cultivars of barley and oat. Yields for the newer cultivars often, but not always, showed similar sensitivity to temperature and precipitation variability and change as was observed for the older cultivars as measured by the adjusted r^2 values. Overall, however, newer cultivars have shown higher yields than the older cultivars, suggesting that breeding programmes have helped to offset the negative impacts of rising temperatures on these cool-season crops.

Projected climate changes for Minnesota (Kunkel *et al.*, 2013) show an increase in spring and summer temperatures, increased winter and spring precipitation, and slight increases in summer precipitation. Our results suggest that higher temperatures in April would be conducive to increased oat yields at Fargo and Brookings but would become detrimental to both oat and barley yield at all sites as they persisted later into the spring and summer. Higher winter and early spring precipitation may enhance yields at some sites but would reduce them at others; increases in summer precipitation, however, reduce yields at all sites where precipitation is an important factor affecting yield. It is possible that the linear relationships between temperature and precipitation changes and changes in barley and oat yield presented here may not be representative of future crop-climate relationships: temperatures exceeding physiological thresholds, for example, can have nonlinear effects on crop yield (e.g., Schlenker and Roberts, 2009) so that the magnitude of future climate change impacts may increase from what has been observed over the past 33 years. Either way, it appears that continued warming of both maximum and minimum temperatures as projected by climate models will be problematic for this region.

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